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DETERMINATION OF VEHICLE ROLLING RESISTANCE AND AERODYNAMIC DRAG

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The retarding forces on a vehicle are characterized by rolling resistance (k_r) and aerodynamic drag (C_dA). These forces determine power requirements for a specified vehicle performance (particularly important for an electric vehicle) and are necessary inputs for any vehicle simulation. Both k_r and C_dA are determined for a number of vehicles and the testing and data analysis techniques are described.

Roll-Down Equations

Straight-line vehicle motion on a level surface is described approximately by

$$F = \frac{W}{21.95}\frac{dv}{dt} + W(k_r + \sin\alpha) + \frac{\rho C_d A}{29.94}(v + w)^2 \quad , \qquad (1)$$

where
- F = road force, pounds
- W = vehicle weight, pounds
- v = vehicle velocity, miles per hour
- w = velocity of wind component parallel to vehicle and in opposite direction, miles per hour
- α = slope, degrees
- t = time, seconds
- k_r = rolling resistance
- ρ = air density, lb/ft^3 (ρ = 0.0766 at 15°C, 1 atm)
- C_d = drag coefficient
- A = frontal area, ft^2.

When the vehicle is coasting, F = 0 and

$$\dot{v} = -21.95(k_r + \sin\alpha) - \frac{\rho C_d A}{1.364W}(v + w)^2 \quad . \qquad (2)$$

For a level surface and no wind, this equation has the solution

$$v = \gamma \tan\beta(t_f - t) \quad , \qquad (3)$$

$$= \frac{\frac{v_o}{\gamma} - \tan\beta t}{1 + \frac{v_o}{\gamma}\tan\beta t} \quad ,$$

where

$$\gamma^2 = 29.94\,\frac{k_r W}{\rho C_d A} \quad ,$$

$$\beta^2 = 16.10\,\frac{\rho k_r\, C_d A}{W} \quad ,$$

$$t_f = \frac{1}{\beta}\tan^{-1}\frac{v_o}{\gamma} \quad .$$

and

v_o = initial coast-down velocity.

Equation (2) indicates that for coast down with constant grade and w = 0, acceleration is a linear function of v^2. Then if acceleration is calculated from the coast-down data and plotted as a function of v^2, the linear regression line can be used to calculate k_r and ρC_dA. The correlation coefficient provides an indication of the quality of the data (provided a reasonably large number of points are used).

If the wind is not negligible, $\dot{v}$ versus v^2 from Eq. (2) departs from a straight line. Ideally, the coast-down tests should be done with no wind; however, program schedules and deadlines rarely permit this luxury when a number of vehicles are to be tested. Therefore, the effects of the wind were analyzed approximately so that corrected values of k_r and C_dA can be obtained. In addition, the wind can be calculated from the coast-down data and compared with the value measured at the time of the run.

When a vehicle is being characterized with coast-down runs, half of the runs should be done in one direction, the other half should be done in the opposite direction. This partially cancels the effects of wind and grade. To illustrate, Fig. 1 shows $\dot{v}$ versus v^2 for a number of east and west runs done with a VW Rabbit. The linear regression lines for each direction are also shown. The different slopes of the east and west regression lines are caused by an east to west wind of approximately 5 mph.

The approximate effects of the wind can be obtained from the east and west coast-down equations, which are

$$-\dot{v}_E = 21.95\,(k_r + \sin\alpha) + \frac{\rho C_d A}{1.364W}(v_E + w)^2 \qquad (4)$$

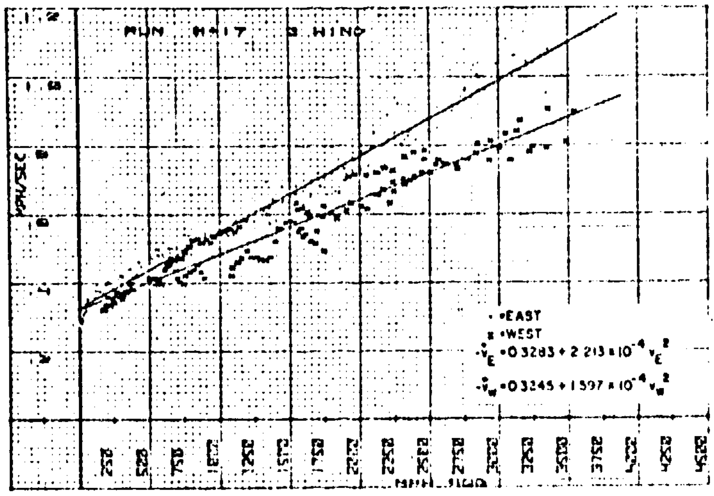

Fig. 1. Acceleration as a function of v^2 for a VW Rabbit.

and

$$-\dot{v}_W = 21.95\,(k_r - \sin\alpha) + \frac{\rho C_d A}{1.364W}\,(v_W - w)^2 \quad . \tag{5}$$

where an east to west wind is positive. If the wind effects are small, Eqs. (4) and (5) can be approximated by

$$-\hat{\dot{v}}_E = B_E + M_E\, v_E^2 \tag{6}$$

and

$$-\hat{\dot{v}}_W = B_W + M_W\, v_W^2 \quad . \tag{7}$$

where the effects of the wind modify the B and M coefficients. If the least square error criterion is used to match Eqs. (6) and (7) with Eqs. (4) and (5),

$$B_E = 21.95(k_r + \sin\alpha) + \frac{\rho C_d A}{1.364W}\left(w + \frac{3}{8}\, v_o\, w\right) \quad , \tag{8}$$

$$B_W = 21.95(k_r - \sin\alpha) + \frac{\rho C_d A}{1.364W}\left(w - \frac{3}{8}\, v_o\, w\right) \quad , \tag{9}$$

$$M_E = \frac{\rho C_d A}{1.364W}\left(1 + \frac{15}{8}\frac{w}{v_o}\right) \quad , \tag{10}$$

and

$$M_W = \frac{\rho C_d A}{1.364W}\left(1 - \frac{15}{8}\frac{w}{v_o}\right) \quad . \tag{11}$$

The B's and M's are the intercepts and slopes of the east and west linear regression lines; the values obtained for the VW Rabbit are given in Fig. 1. Then Eqs. (8) through (11) can be used to determine w, C_dA, and k_r, provided the vehicle weight and air density are known

$$w = \frac{8}{15}\, v_o\, \frac{M_E - M_W}{M_E + M_W} \quad , \tag{12}$$

$$C_dA = \frac{1.364W}{2\rho}\,(M_E + M_W) \quad , \tag{13}$$

and

$$k_r = \frac{B_E + B_W - (M_E + M_W)w^2}{2 \times 21.95} \quad . \tag{14}$$

The coast-down data are then analyzed in the following manner. First, a linear regression analysis is performed on all the east runs and all the west runs (an equal number in each direction should be used). Next, Eqs. (12), (13), and (14) are used to verify the wind velocity then calculate C_dA and k_r. If $\dot{v}$ versus $(v \pm w)^2$ or v^2 is plotted using the correct value of wind, Eqs. (4) and (5) indicate that the east and west regression lines should be parallel. This provides an additional check on the data and the calculations. An example of the process is given in the results section.

Test Procedures

Roll-down tests were conducted on a number of vehicles at the Albuquerque, New Mexico, drag strip. At least four runs were made for each vehicle; one run in each direction from approximately 60 to 35 mph and from approximately 40 to 0 mph. The system used for the tests had a fifth wheel feeding 100 pulses/ft into a microcomputer system.[1] Time is measured to the nearest 0.01 s, velocity to the nearest 0.1 mph, and distance to the nearest foot. Velocity and distance were saved in read/write memory at 1-s intervals, then stored on magnetic tape at the end of each run. The tapes are used as input to plot routines and for data reduction programs that calculate C_dA and k_r.

Extreme care was taken in conducting the coast-down tests so that valid data would be obtained. Vehicles were thoroughly warmed up, weighed, tire pressures checked, windows rolled up, and wind velocity, air temperature, and air pressure were measured. The drag strip was surveyed and the quarter mile section was found to be level (average grade 0.006%, maximum grade 0.07%). The maximum grade was 0.29% at the end of the deceleration track. This would change the acceleration by 0.064 mph/s and, for a 3000-lb car, would change the force by 8.7 lb. This portion of the track was not used for coast-down tests. Equation (10) or (11) shows that a constant wind velocity changes C_dA by a factor

$$1 + \frac{15}{8}\frac{w}{v_o}$$

for a one-way run. For a 5-mph wind and an initial velocity of 60 mph, the factor is 1.156. When the two-way average is taken, this error is substantially eliminated.

It was found that vibration and bounce of the fifth wheel seriously affected th ast-down tests. A substantial effort was made wheel vibration and bounce. A smooth test also an important factor in minimizing vibrat bounce.

Most of the data analysis and r ion was done on a HP-9820A desk calculator with a 9 ink plotter. Both calculator and plotter were taken to the test track so that plots could be obtained and data analyzed on the spot. This provided valuable feedback for evaluating the quality of data obtained and the effects of factors such as wheel bounce, wind, and variations in track grade.

Results

As an example, C_dA and k_r will be calculated for a VW Rabbit from data obtained from the Albuquerque roll-down tests. Five runs were done in each direction and data were saved at 1-s intervals. Figure 2 shows a v versus t plot, corresponding to Eq. (3), for one of the runs. The $\dot{v}$ versus v^2 plot for all 10 runs and the linear regression line for each direction are shown in Fig. 1. In addition, the values of M_E, M_W, B_E, and B_W are given in the equation for $\hat{\dot{v}}_E$ and $\hat{\dot{v}}_W$.

The altitude of the Albuquerque drag strip is 5000 ft, the pressure was 24.9 in. of mercury, and the ambient temperature was 25°C. The density of dry air is

$$\rho = \rho_0(T_0/T)(P/P_0) \quad ,$$

where ρ_0 is a known density at absolute temperature T_0 and pressure P_0. Since

ρ_0 = 0.0766 lb/ft^3 at 15°C, 1 atm (29.92 in. of mercury)

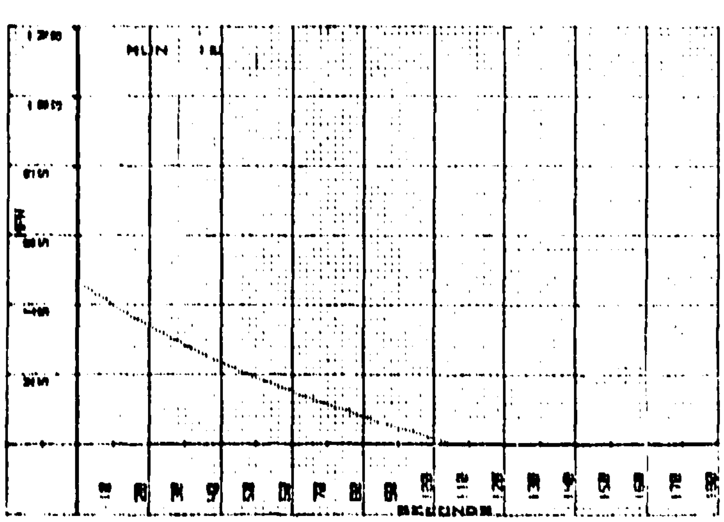

Fig. 2. Coast-down plot for a VW Rabbit.

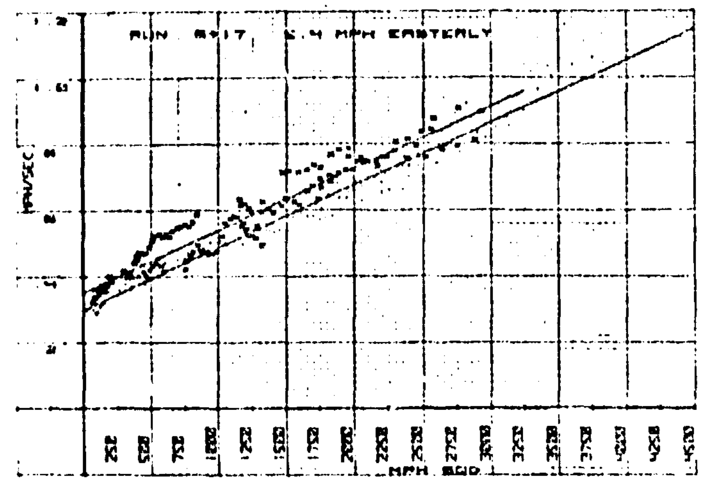

Fig. 3. Acceleration versus v^2 corrected for wind.

the corrected air density is

$$\rho = 0.0766 \times \frac{288}{298} \times \frac{24.9}{29.92} = 0.0616 \text{ lb/ft}^3 \quad .$$

The test weight of the Rabbit was 2500 lb and the initial coast-down velocity was 62.3 mph. Then, using the values in Fig. 1, the calculated wind is

$$w = \frac{8}{15} \times 62.3 \times \frac{2.213 - 1.597}{2.213 + 1.597}$$

$$= 5.37 \text{ mph (east to west).}$$

The aerodynamic drag and rolling friction are

$$C_dA = 10.5$$

$$k_r = \frac{0.6528 - 0.0110}{2 \times 21.95}$$

$$= 0.0146 .$$

It was pointed out above that when $\dot{v}$ versus v^2 is plotted using the correct value of wind, the east and west regression lines should be parallel. Figure 3 shows a plot of $\dot{v}$ versus v^2 and the two regression lines for a 5.4 mph east to west wind.

Acceleration was calculated every second and velocity was measured to the nearest 0.1 mph. This allows a same direction run-to-run variation of 0.2 mph/s. This accounts for much of the scatter in Figs. 1 and 3.

The same technique is used to calculate rolling friction and aerodynamic drag for the other vehicles tested. The results are tabulated in Table I. These results have been used in a technical and economic evaluation of fuel-cell powered vehicles. They have

TABLE I

Vehicle	k_r	C_dA
Honda Accord	0.0166	10.4
VW Rabbit	0.0146	10.5
Ford Granada	0.0164	12.8
Ford Pinto	0.0166	13.6
ElectraVan	0.0183	14.4
Ford Pickup Truck	0.0197	26.7
Air Force Truck (1-1/2-ton Dodge)	0.0142	38.7
Air Force Bus	0.0117	39.2
Toyota	0.0129	11.6
GMC plus Camper	0.0170	56.7
Ford Van	0.0155	24.5

also been used as input to a computer program capable of detailed simulation of a battery-powered or fuel-cell/battery-powered electric vehicle.

Reference

1. D. K. Lynn, C. R. Derouin, and P. Lamar, "Microprocessor-Based System for Roll-Down and Acceleration Tests." to be published in Proc. 29th Vehicular Technology Conf., Arlington, Illinois, March 28-30, 1979.